Measurements of Near Sea Surface Infrared Propagation

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ABSTRACT

A facility to perform spectral atmospheric transmission measurements has been developed. Measurements have been made of the atmospheric infrared transmission near the sea surface. Spectral transmission profiles were measured for a number of ranges using a fourier transform spectrometer. The results have been compared to the predictions of the MODTRAN atmospheric transmission model.

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EXECUTIVE SUMMARY

Atmospheric absorption modulates the infrared radiation emanating from all defence platforms. A proper understanding of atmospheric transmission enables a more precise interpretation to be made of electro-optic measurements. In particular, infrared signature measurements of defence platforms taken at a specific range and under a particular set of atmospheric conditions may be accurately extrapolated for different ranges and conditions.

The near sea surface environment is of particular interest in terms of atmospheric transmission due to its unique aerosol content. Atmospheric transmission in this region is critical to maritime engagements, affecting the performance of weapons and surveillance systems in both littoral and sea scenarios.

Atmospheric transmission measurements have been made using a collimated infrared source and a Fourier transform spectrometer. The measurements were made over a number of ranges and under various atmospheric conditions. The results have been compared with predictions from existing atmospheric transmission models and have shown very good agreement.

The capability now exists to perform atmospheric transmission measurements and these should ideally be performed concurrently with signature measurement activities.

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Shaun Frost joined the DSTO in 1998 after completing a Bachelor of Science Degree majoring in Mathematics and Physics. His present work involves the operation and performance modelling of IR electro-optic systems.

Contents

1. Introduction

1.1 Background

The Signature Measurement and Analysis Group of EWD conducts measurements of defence platform infrared signatures and evaluates electro-optic sensor performance. Such studies are highly influenced by atmospheric effects on the propagation of infrared radiation.

1.2 Aim

The aim of the exercise was to develop the capability for spectral atmospheric transmission measurements and to use this facility to conduct studies into near sea surface propagation in the infrared spectral region.

The capability for such measurements to be made alongside platform signature measurements enables a more precise interpretation of the results. Knowledge of the atmospheric transmission allows signature measurements made at a specific distance to be related back to the source (zero range) in the first instance and then extrapolated to different ranges and atmospheric conditions.

The near sea surface environment is of particular interest in terms of atmospheric transmission due to it's unique aerosol content. Atmospheric transmission in this region is critical to maritime engagements, affecting the performance of weapons and surveillance systems in both littoral and sea scenarios.

The results of the transmission measurements will be compared to the Northern Hemisphere based model, MODTRAN. In this way, the suitability of this model for Southern Hemisphere transmission predictions may be assessed.

2. Instrumentation

2.1 Experimental Layout

The experimental layout consisted of a collimated infrared source as a transmitter and a Fourier transform spectrometer as the receiver. The measurements were made over a number of ranges and under various atmospheric conditions.
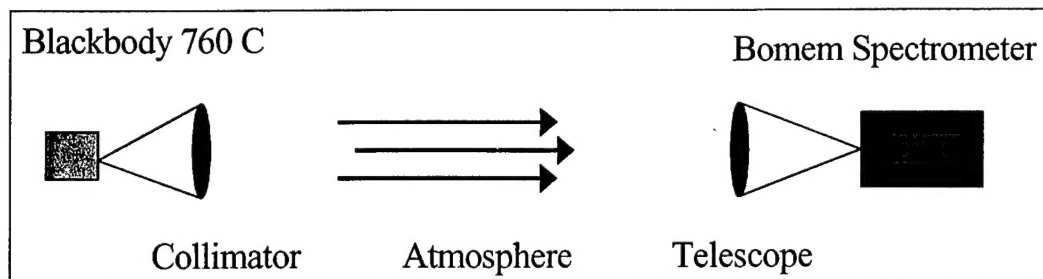
Figure 1: Experimental Layout

A field capable collimator was manufactured at DSTO using a 1 inch commercial blackbody source. The primary mirror is a 254mm gold-plated off-axis parabola with a 1.5 metre focal length. A visible light source and gunsight were included for alignment purposes. A thermocouple was used to monitor the temperature and stability of the blackbody.

Figure 2: Collimator optics.

Figure 3: The collimator.

Figure 4: The Bomem MR254 Spectrometer.

The spectrometer used was the BOMEM MR254 FTIR. This is a dual band system, with an Indium Antimonide (InSb) detector measuring in the $1800 - 5000$ cm^{-1} ($2 - 5.5$ μm) and a Mercury Cadmium Telluride (HgCdTe or MCT) detector measuring in the $500 - 5000$ cm^{-1} 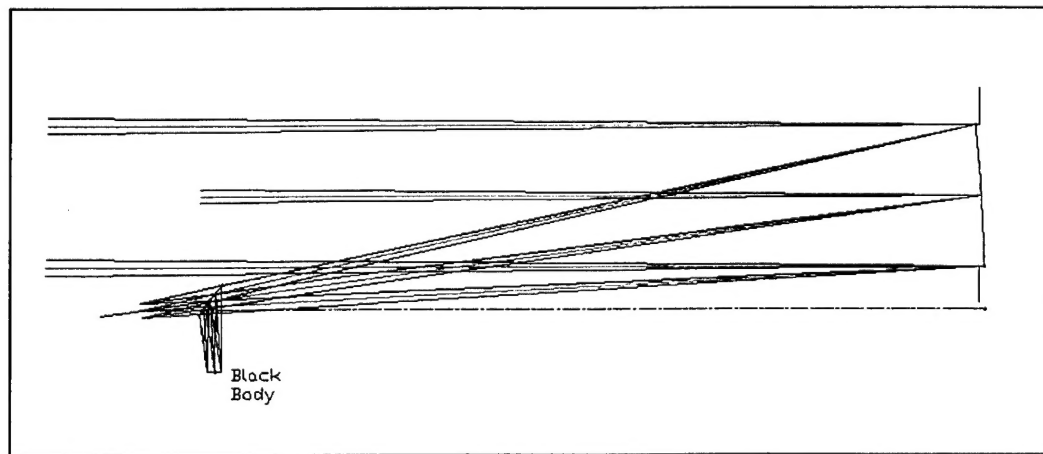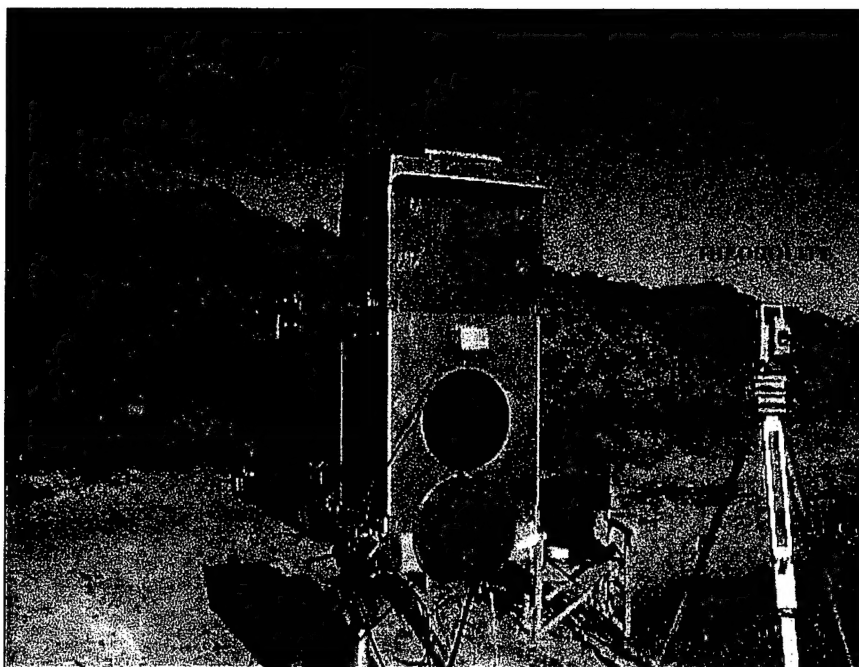($2 - 20$ μm) waveband. Transmission calculations were restricted to the $1800 - 5000$ cm^{-1} waveband due to the higher sensitivity of the InSb detector. The MR254 is a Fourier transform spectrometer. It produces spectra with a 4 cm^{-1} resolution at a scan rate of 31 Hertz. A 10-inch diameter, 3-milliradian FOV telescope was used for all measurements.

2.2 Support Equipment

A weather station was used to monitor barometric pressure, ambient temperature, relative humidity, solar irradiance and wind velocity. A visibility meter recorded visibility, ambient temperature, precipitation (type & quantity), particle count and obstruction to vision (fog or haze). Ranges were measured accurately using a theodolite fitted with a laser rangefinder. A generator was used to provide power for the collimator source and the visibility meter. The spectrometer and its associated computer, camera and monitor were powered by battery packs connected to an inverter. A small generator mounted on the top of the four-wheel drive vehicle powered a second blackbody, which was used for calibrations at each location.

3. Trial Program

3.1 Phase I

Phase I involved laboratory alignment and testing. The collimator was fine tuned until the blackbody and light source were coaxial and at the focal point of the primary mirror.

3.2 Phase II

Phase II involved field assessment of the atmospheric transmission measurement procedure.

In support of an IRST trial, spectral measurements were made across the sea on the 16th of May 1999. These did not involve the collimator, but were made aboard a RAN Guided Missile Frigate (FFG 02 HMAS Canberra). The spectrometer was mounted on the GDP deck of the frigate (Figure 5). Data was acquired from a 700°C source (a 12 inch glow-bar) hanging beneath a RAN Sea King helicopter at various ranges over the Pacific Ocean. This provided some input to the future near sea surface transmission measurements, but low target emissivity compounded by tracking difficulties meant that no meaningful analysis of the results was possible.
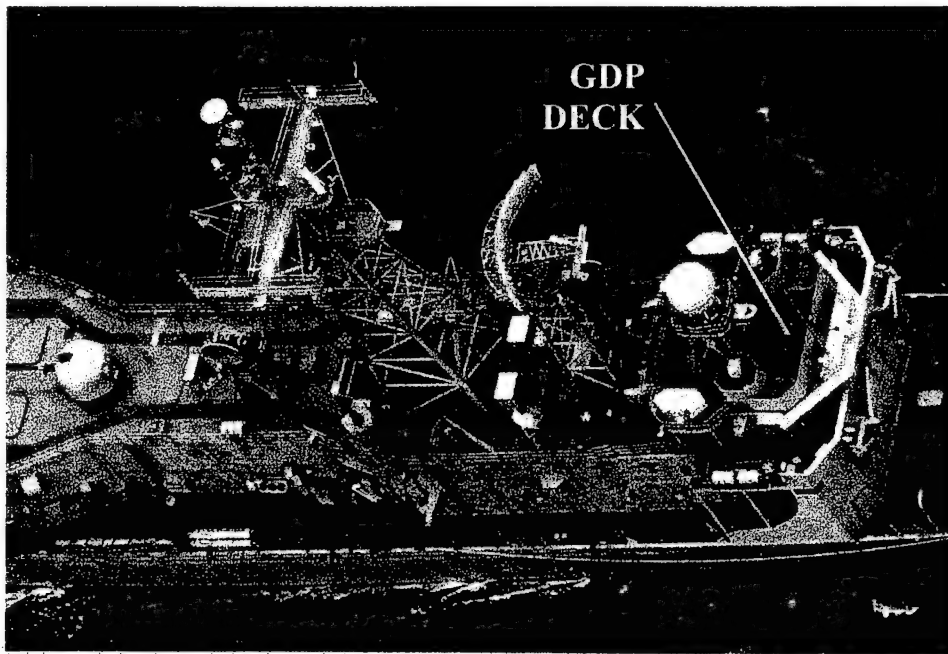
Figure 5: GDP Deck of HMAS Canberra.

Further testing took place in a paddock east of DSTO on the 31st of May 1999. The purpose of this activity was to organise logistics and to verify the set up and alignment methods of the collimator and spectrometer. It also included acquiring data at various ranges (1.0, 1.5, 2.0, 2.5, & 3.0 km), accurately measuring distances, and testing of the analysis methods. Meteorological information was obtained from the nearby Edinburgh RAAF base. The data was analysed, and the processes were proven. The resulting data was compared to MODTRAN.

3.3 Phase III

Phase III involved Near Sea Surface measurements at Pt. Elliot & Middleton beaches, approximately 60 minutes south of Adelaide, on the Southern Ocean. These measurements took place on two separate 3-day trial periods, the 9-11th and 16-18th of June 1999. These trials consisted of land-to-land spectral transmission measurements across water. These beaches were ideal for this purpose due to the curved coastline which enabled various ranges to be attained while maintaining the same collimator (ground zero) site. Data was acquired from three ranges across the sea (667, 1274, 2562m). The corresponding three measurement sites will be referred to as sites 1, 2, and 3 respectively. The altitude was 1.2 meters above the sea surface. There was full weather station support, allowing the analysed data to be compared to MODTRAN predictions. The collimated source and the visibility meter were set up at the ground zero site and the weather station was situated at site 1 so as to be reasonably central to the measurements.
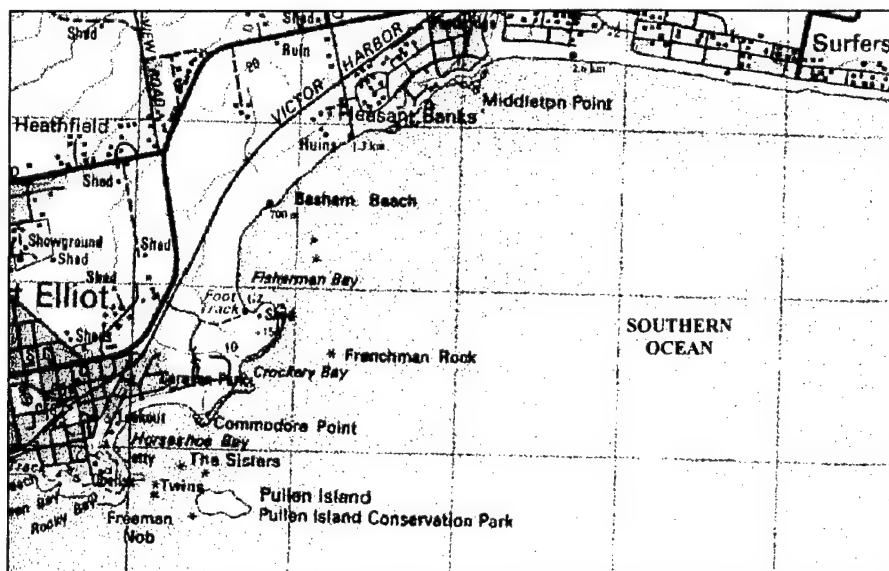
Figure 6: Port Elliot site for NSSP measurements.

Figure 7: Ground zero site.

Figure 8: Site 1. Basham Beach. Spectrometer and weather station.
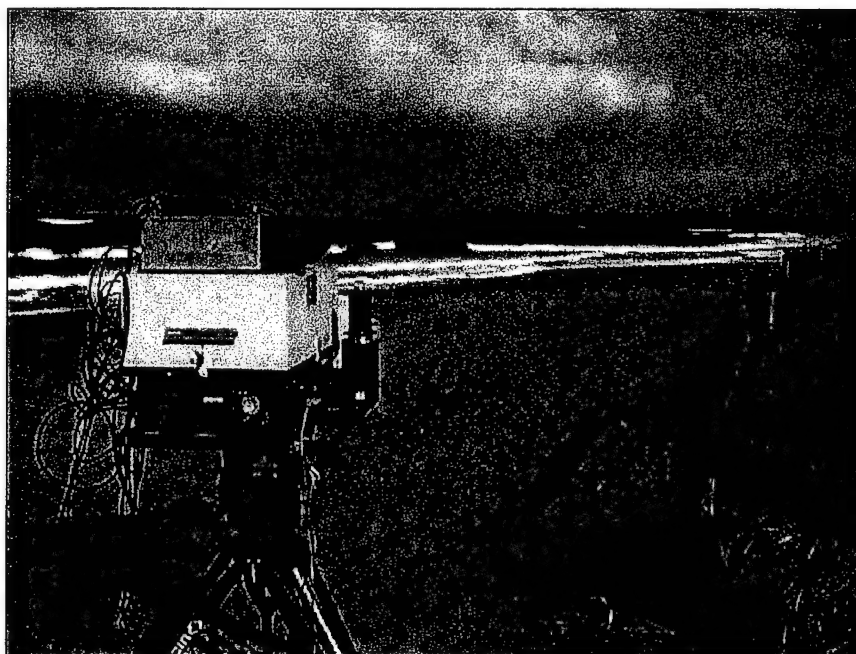

Figure 9: Site 2. Basham Beach.

Figure 10: Site 3. Middleton Beach.

4. Measurement Procedures

Phases I & II brought up some issues that needed to be considered for Phase III. The primary issue was the thermal stabilisation of the spectrometer. It was observed that a one-hour warm up time was required for the device to stabilise. The solution was to leave the spectrometer powered on the entire day for each day of measurements and the detectors were kept cooled with liquid nitrogen. This process ensured that the system responded consistently throughout the day. Battery packs and an inverter enabled this "powered on" condition to be maintained even as the system moved between sites. The spectrometer was placed in the rear of the van during transits and was carried to the beach and placed on a tripod at each site.

Great care was taken to maintain the thermal stability of the spectrometer and to monitor any changes in the system response. This was accomplished through repeated intermediate calibrations. The second blackbody was used for flood-fill calibrations (the spectrometer aperture being filled by the blackbody aperture) before and after each measurement. Thermocouples were used to monitor the temperature of both the collimator blackbody and the secondary blackbody used for intermediate calibrations.

A zero range measurement was made with the spectrometer right up against the collimator, followed by sequential range measurements.
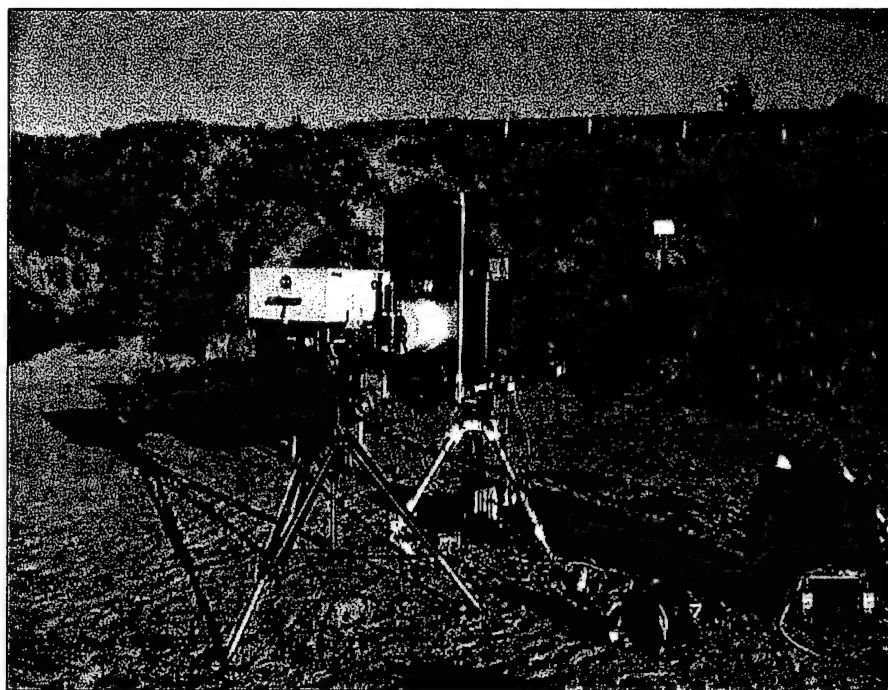

Figure 11:   Zero range measurement.

A co-addition facility in the acquiring software was utilised, enabling spectra to be averaged over time to reduce noise and other transient effects. For this test, the scans were averaged over an 80-second time interval.

For each measurement a background spectrum was acquired for subtraction, with the blackbody source blocked internally to minimise changes to the scene observed by the spectrometer.

5. Analysis Methodology

The blackbody source in the collimator is not a point source, so there is some divergence of the emerging radiation. This is commonly referred to as the searchlight effect. Rays from the centre of the blackbody aperture emerge in the direction of the optical axis, while rays from the edge of the blackbody aperture emerge in a parallel beam at an angle to the optic axis.   The two regions of interest to us are the near field and far field (labelled I and II in Figure 12). In region I, the apparent image of the blackbody source is smaller than the collimator mirror and because the entire source can be seen and the image is at infinity, the irradiance observed is constant throughout this region. However, in region II, the source appears larger than the mirror and the mirror essentially acts as a stop. This causes the collimator to behave as a point source and hence the irradiance observed in region II drops off as the inverse square of the

distance from the collimator. Thus the effect of the collimator is to make the blackbody appear as a much more intense point source.
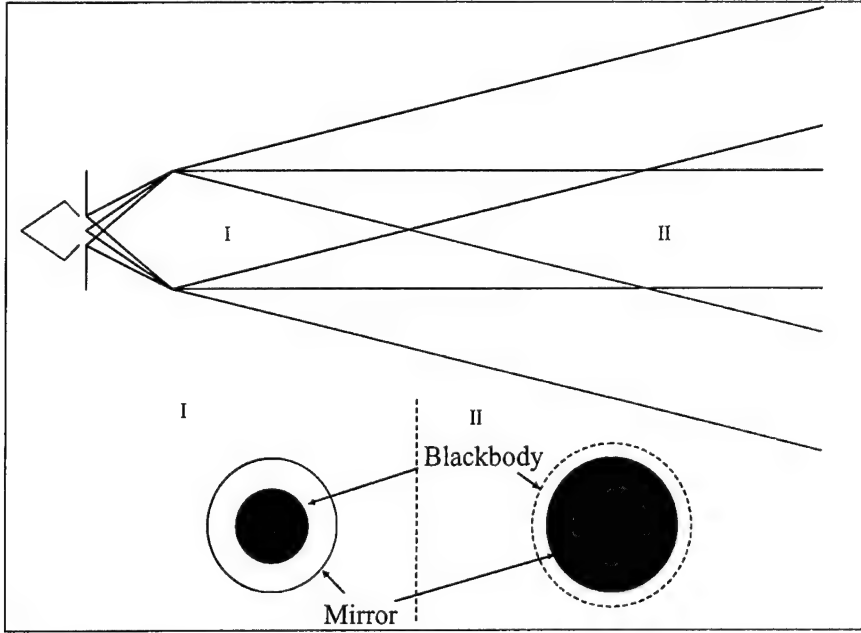

Figure 12:   Searchlight Effect.

The collimator can be considered as a Lambertian Source and hence the radiance is constant along the optic axis except for the atmospheric transmission factor.   The atmospheric transmission can thus be found by simply dividing the distance radiance measurement by the zero range radiance measurement.   However, the spectrometer essentially measures irradiance arriving at the detectors, not radiance. To correct for this, the formulae listed below are utilised.

$$L_{DIST}(\lambda) = \frac{E_{DIST}(\lambda)d^2}{A_C} \tag{1}$$

$$L_{ZERO}(\lambda) = \frac{E_{ZERO}(\lambda)f^2}{A_S} \tag{2}$$

$$\tau_{ATM}(\lambda) = \frac{L_{DIST}(\lambda)}{L_{ZERO}(\lambda)} \tag{3}$$

where $L_{DIST}(\lambda)$ is the radiance arriving at the spectrometer for any far field measurement,

$E_{DIST}(\lambda)$ is the corresponding irradiance measured at the spectrometer,

d   is the corresponding distance between the collimator and the spectrometer,

A_c is the area of the collimator primary mirror,

$L_{ZERO}(\lambda)$ is the radiance leaving the collimator,

$E_{ZERO}(\lambda)$ is the corresponding irradiance measured at the spectrometer in the ground zero measurement,

f is the focal length of the collimator,

A_s is the area of the black body source within the collimator,

$\tau_{ATM}(\lambda)$ is the corresponding atmospheric transmission.

In the far field, the relevant solid angle (A/d^2) is that of the collimator mirror at the distance involved, but in the near field, since the entire source can be seen, it is the solid angle subtended by the blackbody source at the focal length that is important.

The radiance from the blackbody will obviously be modulated by the transmission of the collimator optics and further by the transmission of the spectrometer telescope, but since these factors are inherent in both zero range and far field measurements, they cancel in the division through which atmospheric transmission is calculated.

6. Results

The plot shown in *Figure 13* was created from data taken from the Phase III measurements. It shows a spectral comparison between the theoretical 760°C blackbody radiance curve, the measured radiance at the front of the collimator and the measured radiance at a range of 667 meters. Some measured atmospheric transmissions from the DSTO paddock and Port Elliot are displayed in Figures 14 - 17. The data correlates well except for consistently larger values in the 2400 to 2800 wavenumber region for all of the ranges. There also appears to be a shoulder at 2400 cm^{-1} in the MODTRAN curve that is not in the measured curve.
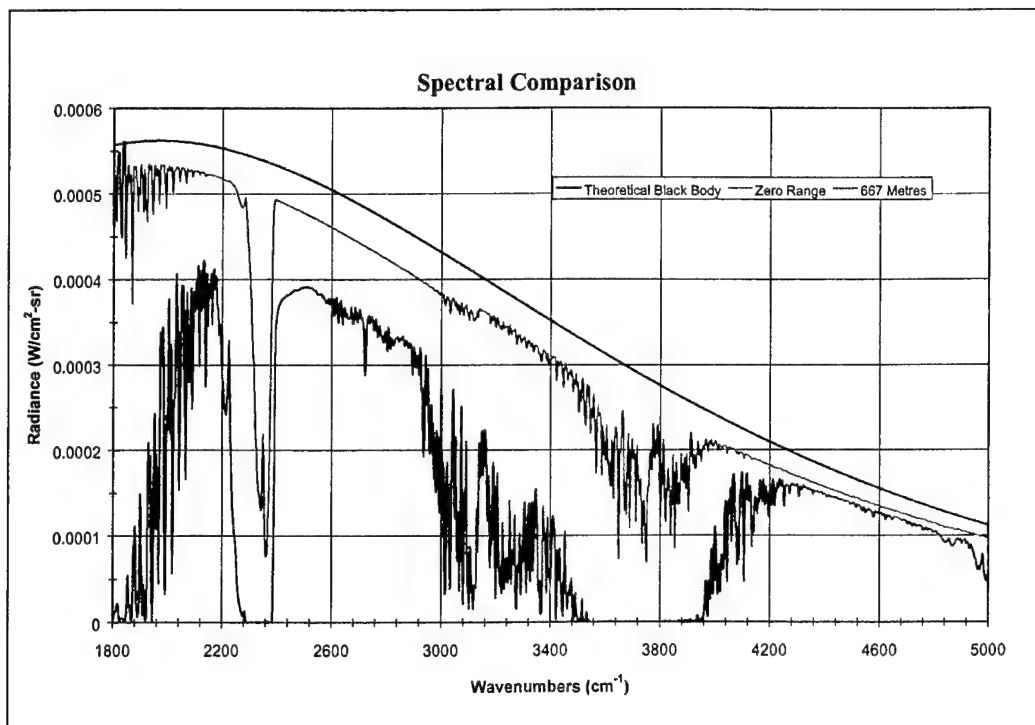
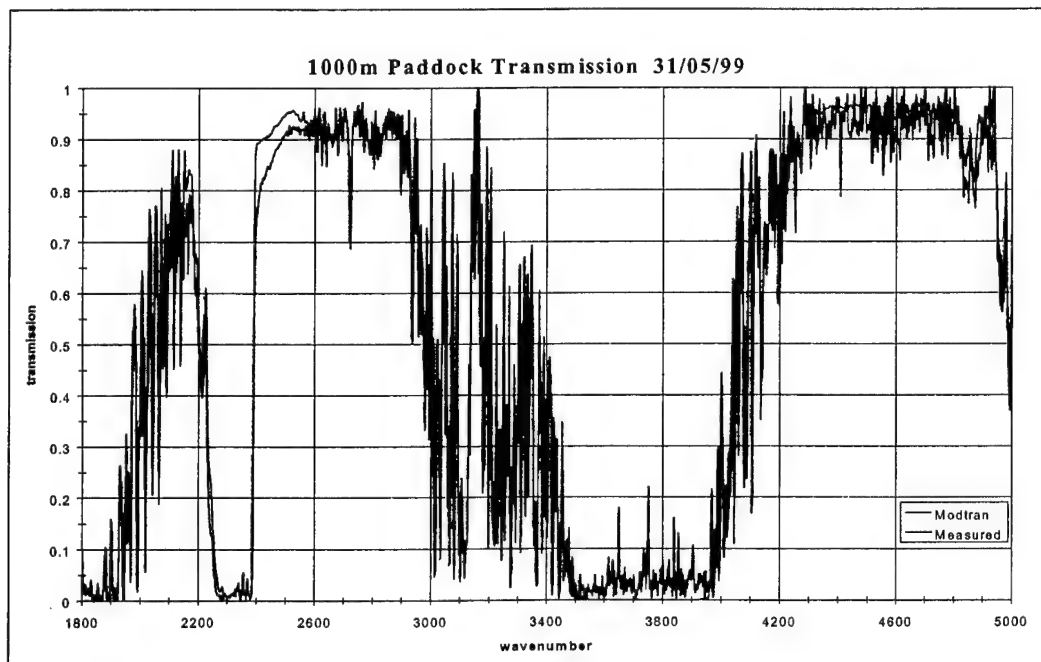*Figure 13:   Comparison of theoretical and measured spectra.*

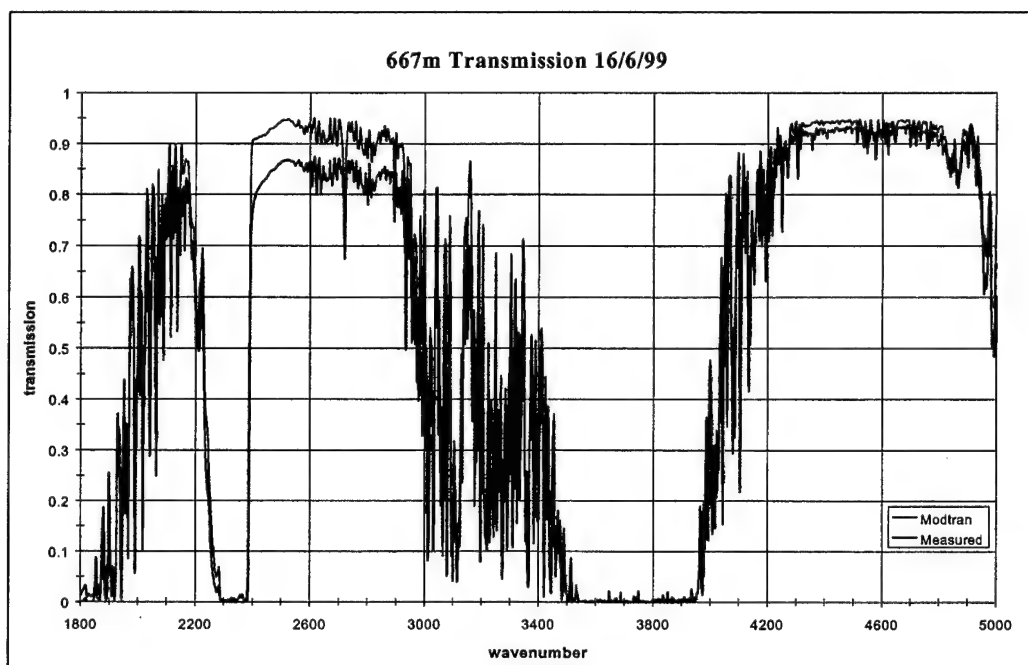*Figure 14:   DSTO paddock transmission (1000 m).*

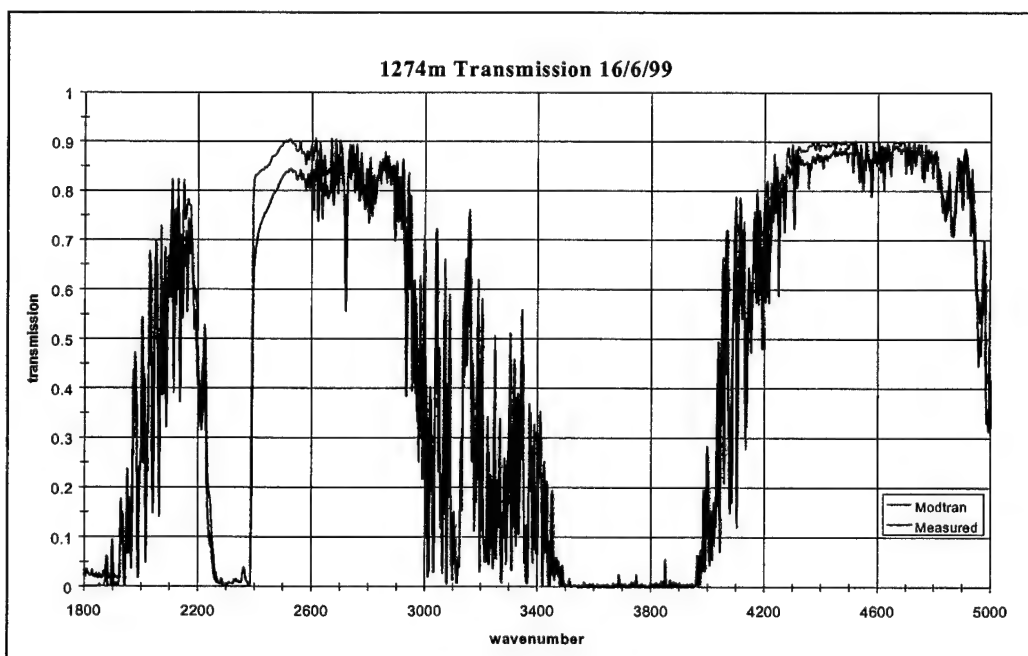Figure 15: *Near sea surface transmission (667 m).*

Figure 16: *Near sea surface transmission (1274 m).*
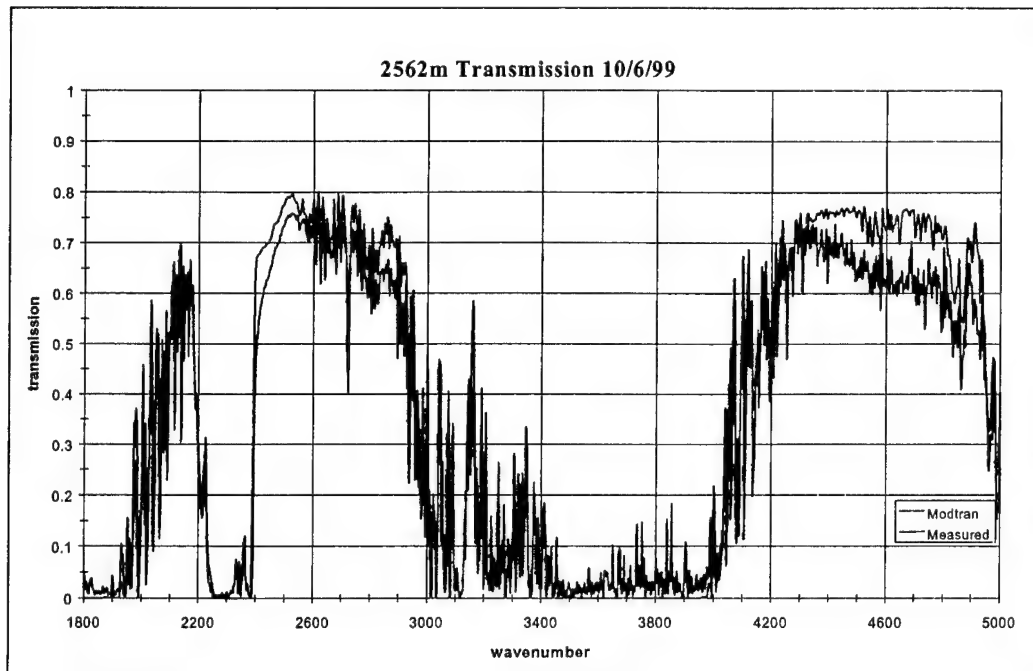
Figure 17:   Near sea surface transmission (2562 m).

7. Conclusions

An atmospheric transmission measurement capability now exists as part of the SMA group in EWD at DSTO Salisbury. Preliminary studies indicate reasonable accuracy from MODTRAN under the conditions encountered, provided accurate meteorological information is recorded. MODTRAN was developed using data collected from the Northern Hemisphere and hence the regional meteorological models provided are not directly applicable. An indication of the MODTRAN output variation for different meteorological models is given in *Figure 18*, 'actual' represents the MODTRAN output when the recorded meteorological data is used. Measurement of atmospheric visibility is also crucial to achieving accurate MODTRAN output. *Figure 19* displays MODTRAN output for two aerosol model visibilities, 'Maritime' with visibility 56 km and 'Navy Maritime' with visibility 23 km. These were calculated for a range of 1274 metres. Further studies will be needed to ascertain whether MODTRAN needs to be updated for Southern Hemisphere aerosol models in order to correct for deviation from measured transmissions.
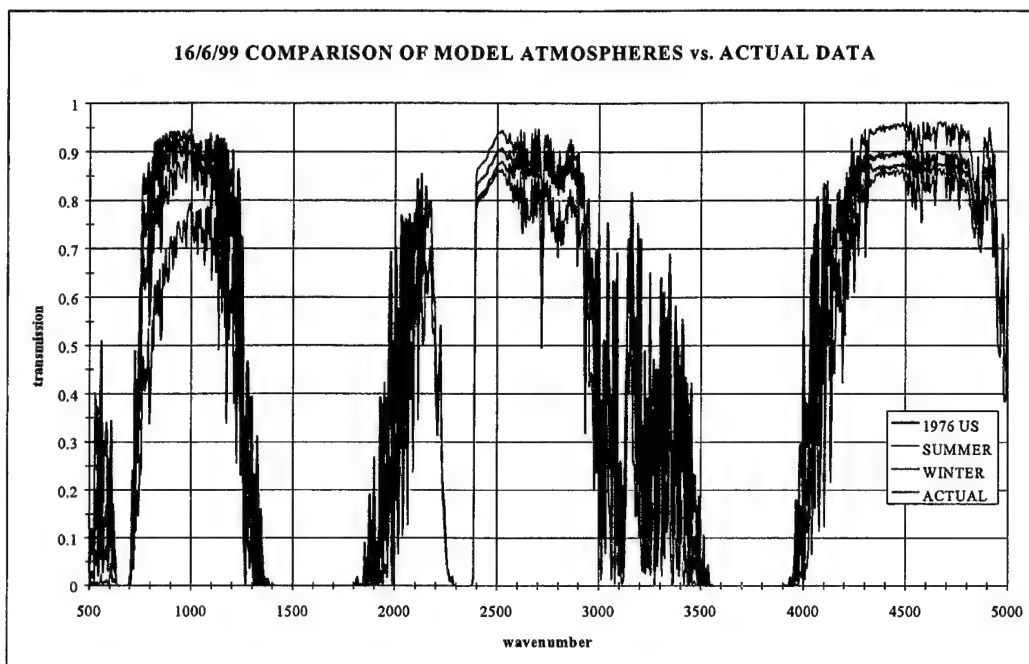
Figure 18: MODTRAN output variation for different meteorological conditions.
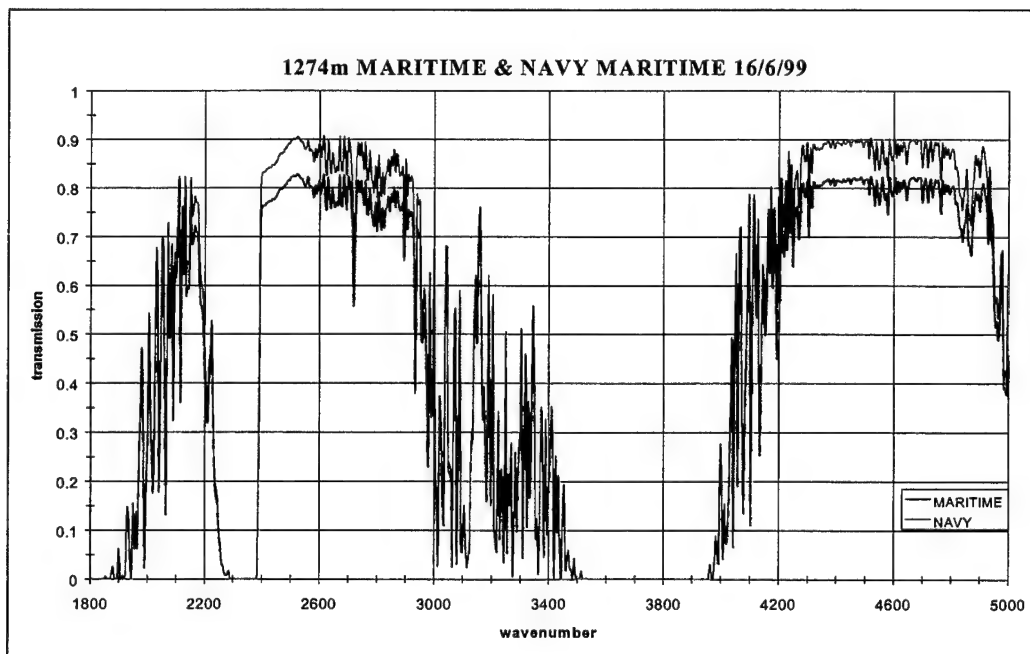
Figure 19: MODTRAN output variation for different visibilities.

8. Glossary

DSTO	Defence Science and Technology Organisation
EWD	Electronic Warfare Division
GDP	Gun Director's Platform
HMAS	Her Majesty's Australian Ship
IRST	Infrared Search and Track
RAAF	Royal Australian Air Force
RAN	Royal Australian Navy
SMA	Signature Measurement and Analysis

Appendix A: Calibration Analysis for Bomem MR254 Spectrometer

In order to calibrate the spectrometer, a blackbody radiator (calibrated to National Standards at the National Measurement Laboratory, Lindfield, NSW) is placed immediately in front of the spectrometer aperture in order to flood fill the device. Measurements are taken in this arrangement for two different blackbody temperatures. The theoretical radiance is given by:

$$L_U(v) = \frac{c_1 v^3}{\pi \left(e^{\frac{c_2 v}{T_U}} - 1 \right)}$$

A(1)

$$L_L(v) = \frac{c_1 v^3}{\pi \left(e^{\frac{c_2 v}{T_L}} - 1 \right)}$$

A(2)

where: $L_U(v)$ is the theoretical blackbody radiance for the upper temperature,

$L_L(v)$ is the theoretical blackbody radiance for the lower temperature,

v is the wavenumber in units of cm^{-1},

T_U, T_L are the upper and lower temperatures respectively and

C_1, C_2 are the first and second radiation constants:

$C_1 = 3.7415 \times 10^{-12}$ [W/cm^2 /cm^{-1}]

$C_2 = 1.43879$ [cm K].

The spectrometer signal is given by:

$$V(v) = G(v)L(v) + O(v)$$

A(3)

where: $V(v)$ is the spectrometer voltage output,

$G(v)$ is the instrument gain and

$O(v)$ is the instrument offset.

Hence the instrument gain and offset are determined as follows:

$$G(v) = \frac{V_U(v) - V_L(v)}{L_U(v) - L_L(v)} \tag{A(4)}$$

$$O(v) = V_U(v) - G(v)L_U(v) = V_L(v) - G(v)L_L(v) \tag{A(5)}$$

All subsequent measurements are converted from voltage output to radiance using the following relation:

$$L(v) = \frac{V(v) - O(v)}{G(v)} \tag{A(6)}$$

The radiance measurement can then be converted to apparent radiant intensity or irradiance as desired:

$$I(v) = L(v)A_S \tag{A(7)}$$

$$E(v) = \frac{L(v)A_S}{d^2} \tag{A(8)}$$

where: $I(v)$ is the apparent radiant intensity observed,

$E(v)$ is the irradiance observed,

A_S is the projected area of view of the telescope used at the range of the target, and

d   is the distance between the source and the spectrometer.

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19. ABSTRACT

A facility to perform spectral atmospheric transmission measurements has been developed. Measurements have been made of the atmospheric infrared transmission near the sea surface. Spectral transmission profiles were measured for a number of ranges using a fourier transform spectrometer. The results have been compared to the predictions of the MODTRAN atmospheric transmission model.